GPS Navigation above 76,000km for the MMS mission

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39th Annual AAS Guidance, Navigation and Control Conference
February 8, 2016

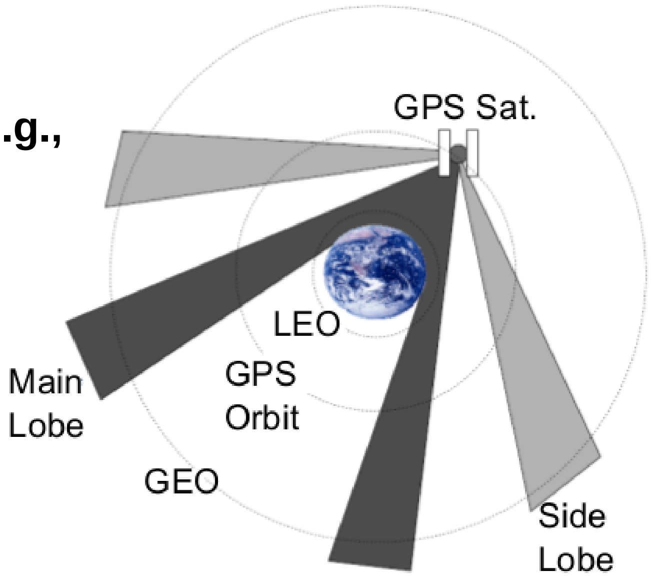
Outline

- **Background on high altitude GPS**
- **GSFC Navigator GPS receiver**
- **GPS Navigation for the MMS mission**
  - MMS mission
  - MMS navigation system
  - Performance results from MMS Phase 1
  - Value of sidelobes
  - Predicted performance in MMS Phase 2
- **Summary**

Background on high-altitude (HEO) GPS

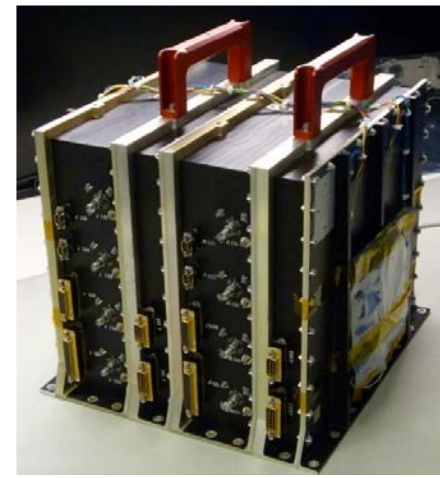
- **HEO GPS navigation offers performance and cost improvements, but poses challenges**
  - Sparse mainlobe availability, sidelobes weak, unspecified/uncharacterized, harsher radiation environment.
- **Ongoing research in HEO GPS R&D since 1990's, GSFC among leaders**
  - Numerous simulations studies, indicate excellent performance at GEO, HEO, lunar distances
  - GSFC led effort to define/expand GPS Space Service Volume definition and characterize in-situ patterns (GPS-ACE 2015)
  - Developing Navigator HEO GPS receiver
- **Early on-orbit experiments in late 1990's-early 2000's**
  - AFRL Falcon Gold, TEAMSAT, EQUATOR-S
  - NASA GSFC / AMSAT OSCAR-40, 2000
- **Recent growth in available receivers/applications, e.g.,**
  - GD Monarch flying on USG SBIRS (GEO) (~2011-2012)
  - Surrey Satellite SGR-GEO experiment on GIOVE-A (2013)
  - Airbus/Astrium MosiacGNSS and LION GNSS Rx for HEO
  - Moog-Broad Reach Navigator (AFRL ANGELS 2015, EAGLE 2017)
  - General Dynamics' Viceroy-4 to fly on GOES-R (2016)
  - RUAG Podrix to fly on ESA Proba-3 (2018)
  - ***NASA GSFC Navigator GPS flying on HEO MMS 2015***

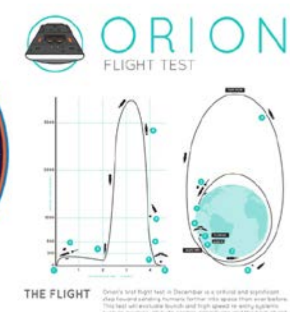
High-altitude GPS



Navigator GPS Receiver

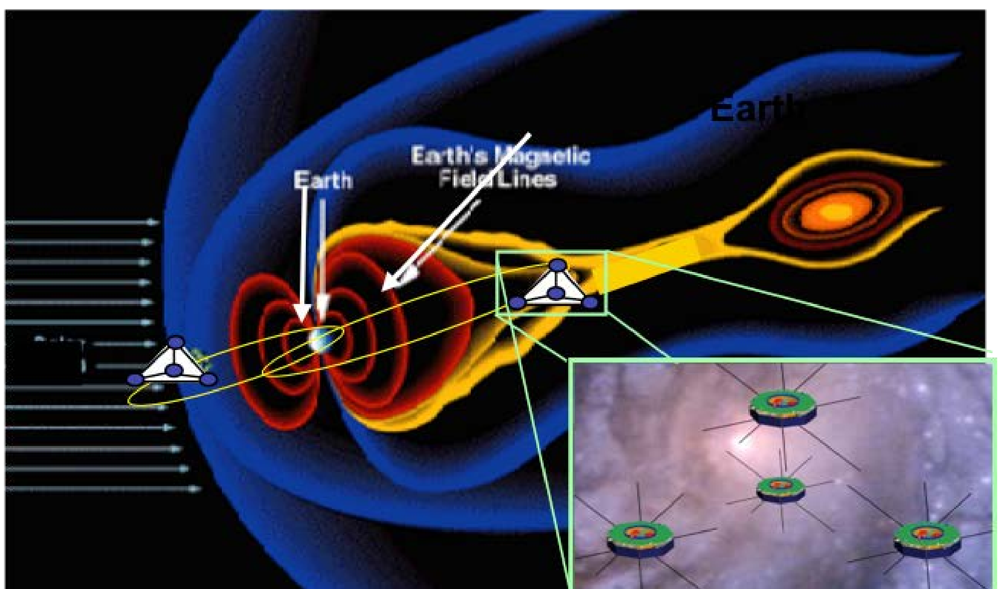
- **Legacy Navigator**
  - C/A code receiver
  - ~10m level onboard accuracy for LEO/GEO/HEO
- **Performance for high altitude applications enabled by**
  - *Fast, unaided* weak signal acq. and tracking (<25 dB-Hz)
  - Integrated on-board navigation filter (GEONS)
  - Radiation hardened
- **Early demonstration on Hubble Space Telescope Servicing Mission 4 STS-125 (May 2009)**
  - Captured unique reflected GPS dataset
- **Global Precipitation Measurement Mission (Feb 2014)**
  - First operational use of Navigator
- **Orion EFT-1 (Dec 2014)**
  - Navigator technology integrated in Honeywell GPS receiver
  - ***Fast acquisition of GPS signals*** benefits navigation recovery after re-entry radio blackout without relying on IMU, stored states.
- **Magnetospheric Multiscale Mission (March 2015)**
  - ***<u>Currently represents the highest (and fastest) GPS receiver operations</u>***





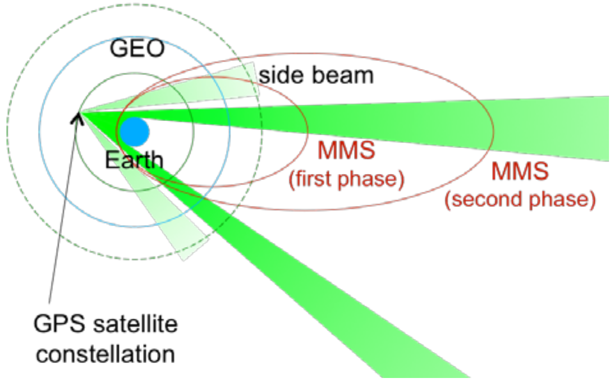
Magnetospheric MultiScale Mission (MMS)

- **Discover the fundamental plasma physics process of reconnection in the Earth's magnetosphere.**
- **Coordinated measurements from tetrahedral formation of four spacecraft with scale sizes from 400km to 10km**
- **Flying in two highly elliptic orbits in two mission phases**
  - Phase 1 1.2x12 R_E (magnetopause)
  - Phase 2B 1.2x25 R_E (magnetotail)



MMS Navigation

- **MMS baselined GSFC Navigator + GEONS Orbit Determination (OD) filter software as sole means of navigation (mid 2000's)**
  - Original design included crosslink, later descoped



- **Trade vs. Ground OD (2005)**
  - Estimated >$2.4M lifecycle savings over ground-based OD.
  - Enhanced flexibility wrt maneuver support
  - Quicker return to science after maneuvers
- **Main challenge #1: Sparse, weak, poorly characterized signal signal environment**
  - MMS Navigator acquires and tracks below 25dB-Hz (around -178dBW)
  - GEONS navigation filter runs embedded on the Navigator processor
  - Ultra stable crystal oscillator (Freq. Electronics, Inc.) supports filter propagation
- **Main challenge #2: Spacecraft are spin stabilized at 3RPM with obstructions on top and bottom of spacecraft**
  - Four GPS antennas with independent front end electronics placed around perimeter achieve full sky coverage with low noise
  - Receiver designed to hand off from one antenna to next every 5s

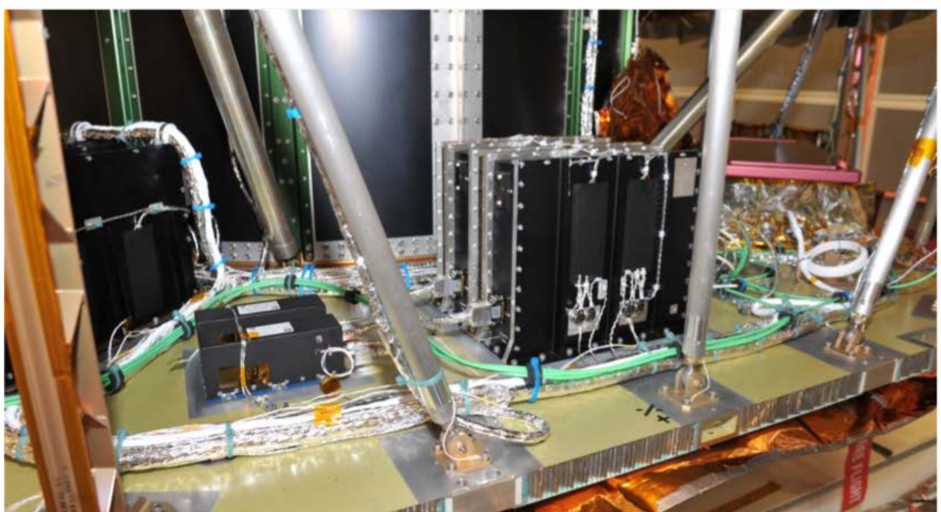
MMS Navigator GPS hardware

- GPS hardware all developed and tested at GSFC. Altogether, 8 electronics boxes, 8 USOs, 32 antennas and front ends

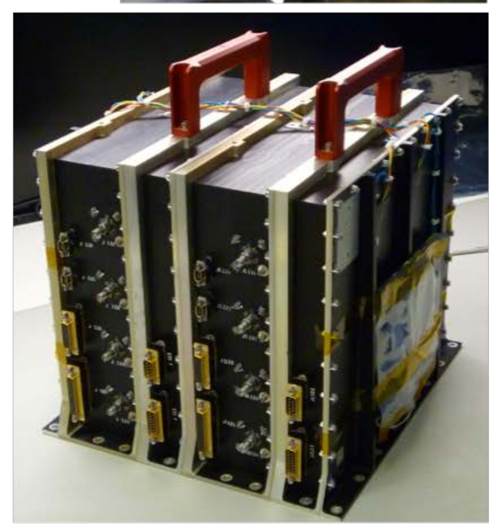
Ultra Stable Osc.

Front end electronics assembly

GPS antenna



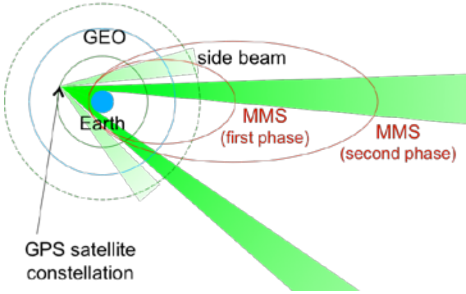
Receiver and USO on spacecraft deck



Redundant receiver electronics

Goddard's Enhanced Onboard Navigation System (GEONS)

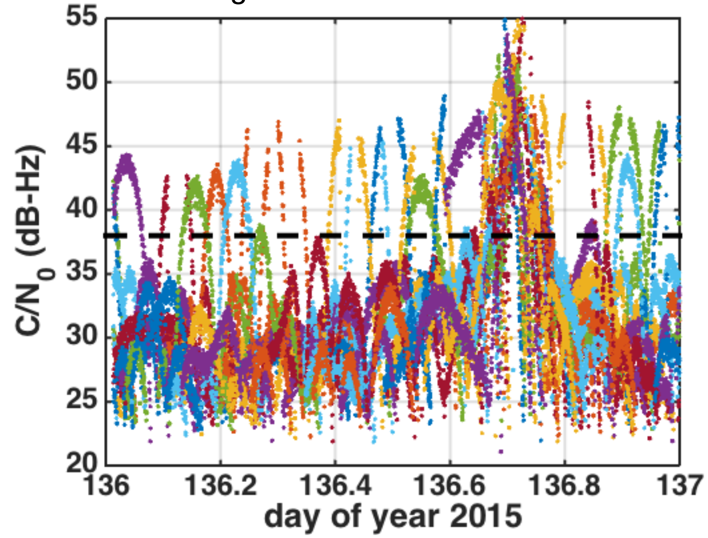
- **UD-factorized Extended Kalman Filter, 4th/8th order RK integrator, realistic process noise models**
- **Estimation state:** Absolute and/or relative position and velocity vectors for multiple satellites, clock states, drag and SRP coeff corrections, measurement biases
- **Dynamic models:** High fidelity geopotential, solar system bodies, Harris-Priester atmospheric density, SRP with spherical or multi-plate area models, measured accelerations, impulsive delta-V maneuver model
- **Measurement types:** GPS differenced/undifferenced, WAAS, differential corrections, TDRSS, Ground station, Crosslink, Celestial object line of sight, XNAV
- **Development history**
  - Ground-based experiments on Landsats 4 & 5, COBE (1980s) onboard exp. EUVE (1990s)
  - TDRSS Onboard Navigation System (TONS): operational onboard OD for Terra 1999-current
  - Enhanced Onboard Navigation System (EONS) = TONS + GS meas on GD Command Receiver
  - Celnav tested on the ground with POLAR and SOHO data
  - TONS -> GPS for GPS Enhanced Orbit Determination Experiment (GEODE) on Lewis (1996), follow on EO-1 and licensed to industry flown on Microstars, Orbviews, SORCE, CALIPSO ++
  - XNAV measurement model added for NICER/SEXTANT demonstration (2016 launch)
  - **GEONS = GEODE + EONS + Celnav + XNAV**
- **MMS GEONS**
  - Estimate absolute pos/vel, clock bias, rate & accel, integrator step 10s
  - 13x13 geopotential, sun, moon point mass, SRP, drag
  - Process L1 C/A GPS undifferenced pseudorange at 30s rate
  - Accelerometer data at 10s during maneuver



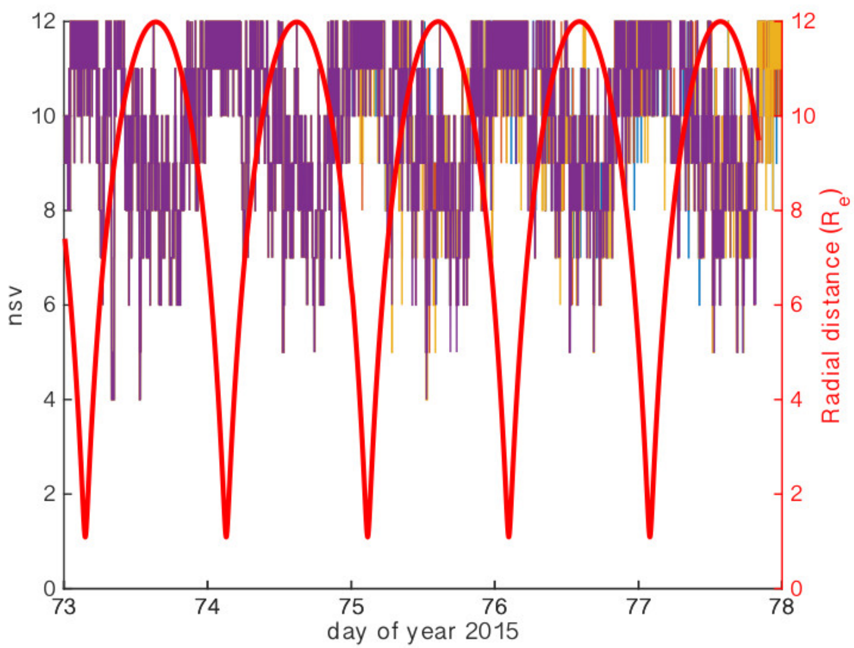
Phase 1 Performance: signal tracking

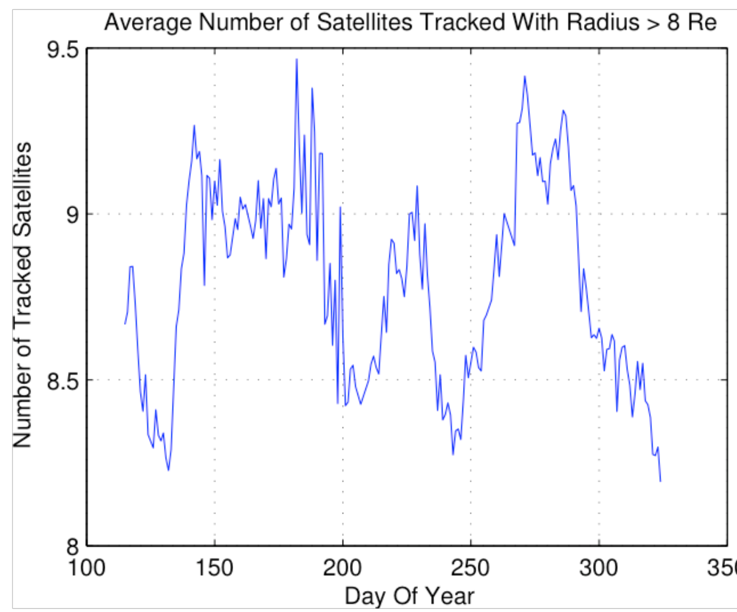
- Once powered, receiver began acquiring weak signals and forming point solutions
- Long term trend shows average of >8 signals tracked above $8R_E$
- Above GPS constellation, vast majority of these are sidelobe signals
- Visibility exceeded preflight expectations

Signal to noise vs. time



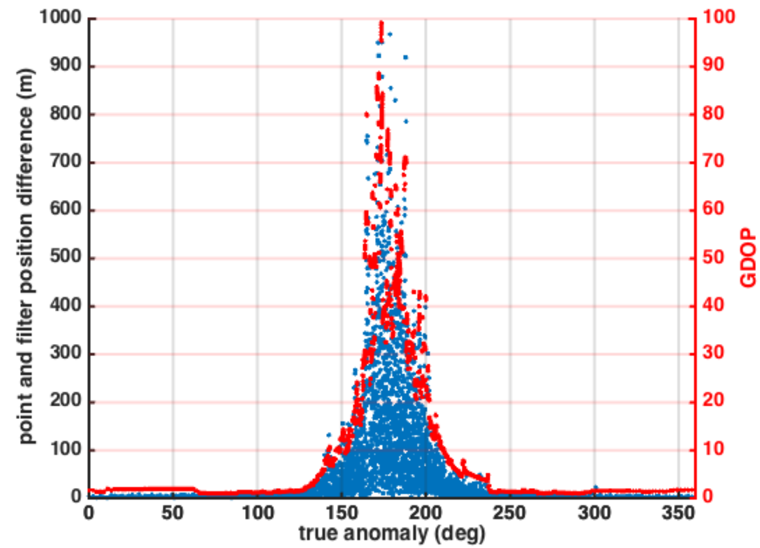
Signals tracked during first few orbits

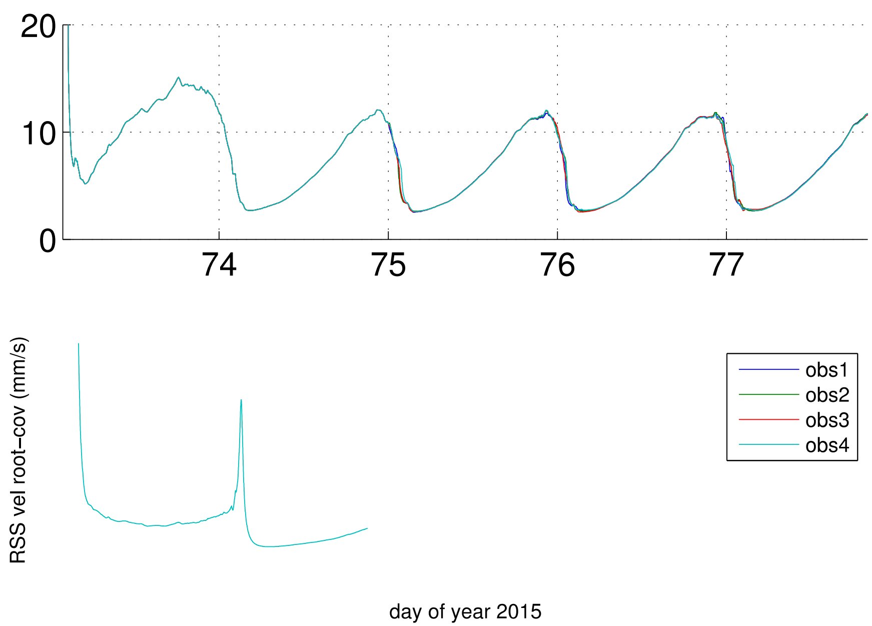


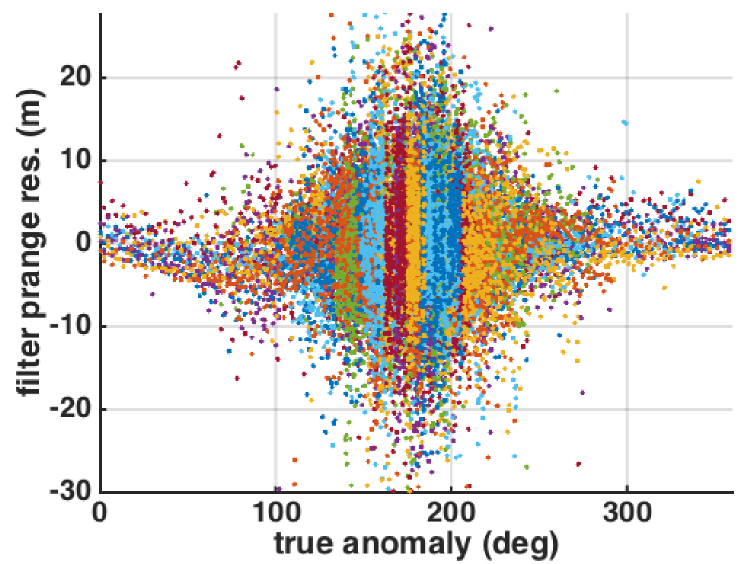


Phase 1 results: measurement and navigation performance

- GEONS filter RSS 1-sigma formal errors reach maximum of 12m and 3mm/s (typically <1mm/s)
- Although geometry becomes seriously degraded at apogee, point solutions almost continuously available
- Measurement residuals are zero mean, of expected variation. Suggests sidelobe measurements are of high quality.





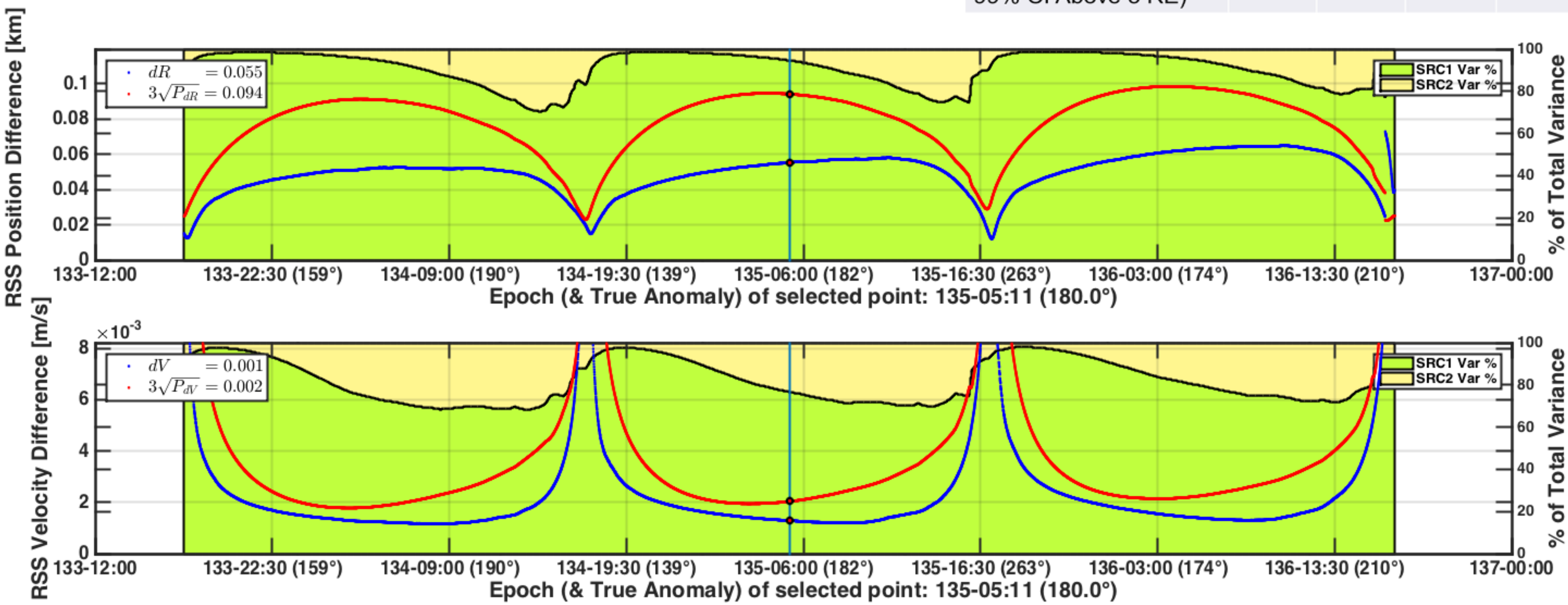


Navigation commissioning

- **Certification campaign from day of year 133 to 137: no maneuvers, increased TDRSS and DSN measurement schedule**
- **GSFC Flight Dynamics Facility performed independent OD using TDRSS/DSN radiometrics**
- **Plot shows MMS1 orbit difference and 3-sigma total variance along with component variance fractions.**
  - FDF is, by far, largest contributor to total variance.

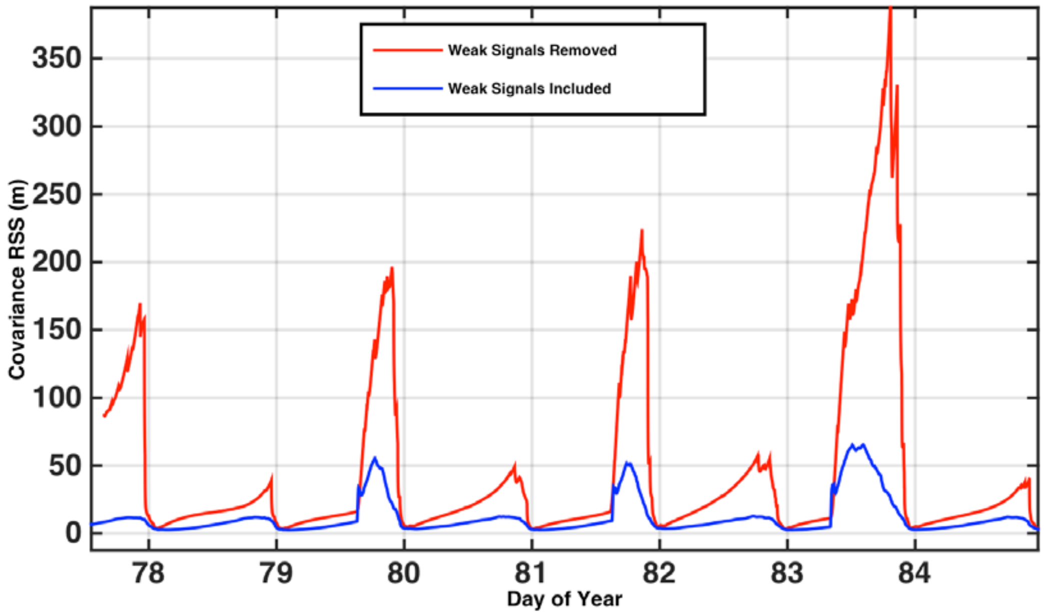
- MMS requirements: 100km absolute position accuracy (needed for science)
- 50m (99%) SMA knowledge above 3Re and outside maneuver recovery (for formation maintenance)

FDF V02	MMS1	MMS2	MMS3	MMS4
Maximum Difference in RSS Position	65 m	50 m	50 m	25 m
SMA Difference (Max of 99% CI Above 3 RE)	< 4 m	< 5 m	< 6 m	< 4 m



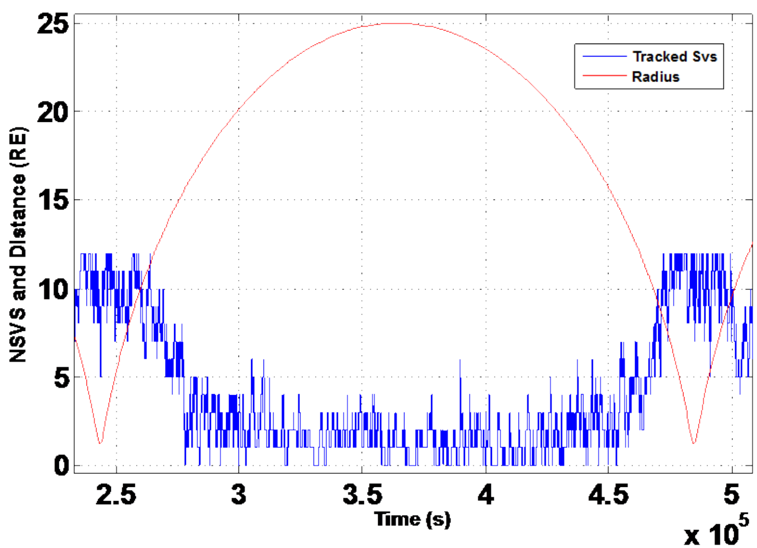
Value of sidelobes for MMS

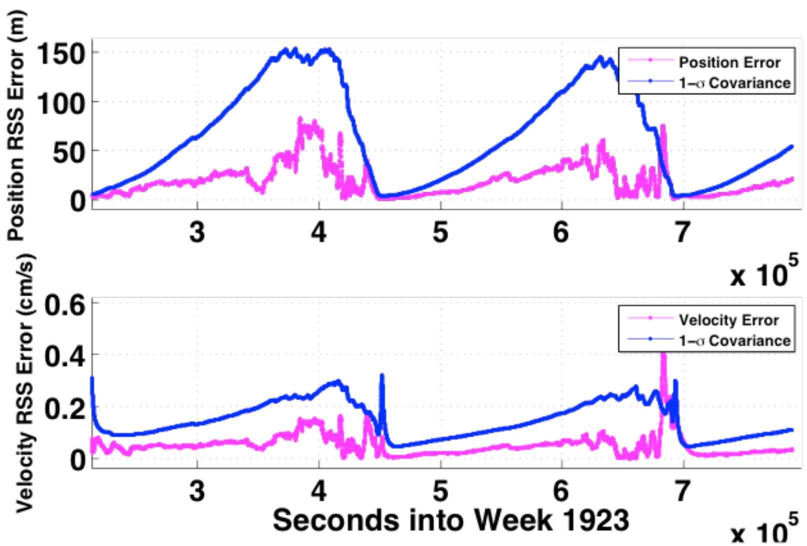
- **Simulation study looked at reprocessing flight measurements from MMS Phase 1 through Navigator FSW (w/GEONS) on ground, compared:**
  - Processing all data (matching on-orbit results) in blue
  - Removed signals below 38dB-Hz simulating removal of side-lobes in red
- **Dataset includes early sequence of four perigee raising maneuvers**
  - Process noise inflated during maneuver window, accelerometer data passed to GEONS
- ***Sidelobes significantly improve initial convergence, peak errors at apogee and maneuver recovery***



Phase 2B predicted performance

- **It has become apparent that the MMS preflight simulations had significant conservatism built in.**
- **Recalibrated MMS Phase 2B hardware-in-the-loop simulations conducted in GPS test lab (FFTB) with MMS EM show improved performance**





Summary, Future Work

- **High altitude GPS is now a proven technology that can reduce operations costs and even enable missions like MMS.**
  - Applications and receiver availability expanding rapidly
- **MMS currently in Phase 1 orbit at 12Re (almost twice GEO distance) navigating onboard with GPS using GSFC-Navigator receiver with GEONS filter software**
  - *Highest (and fastest) operational use of GPS*
  - Onboard navigation significantly exceeding requirements
  - Signal visibility throughout Phase 1 orbit is excellent
  - Sidelobe signals are of “navigation quality”
  - Promising for MMS Phase 2B with 25Re apogee, and future mission
- **GSFC continues to conduct high-altitude GPS R&D**
  - Next Generation Navigator in development
    - Modernized, Multi-frequency, multi-GNSS, reduced SWaP
    - Real-time navigation at GEO in “bent-pipe” mode for GPS-ACE project (2014)
    - First on-orbit use for TASS (TDRSS beacon) demonstration on STP-H6 (2018)
  - Leading efforts to protect and characterize GPS signals for high-altitude users
  - Maintains world-class test facility and expertise